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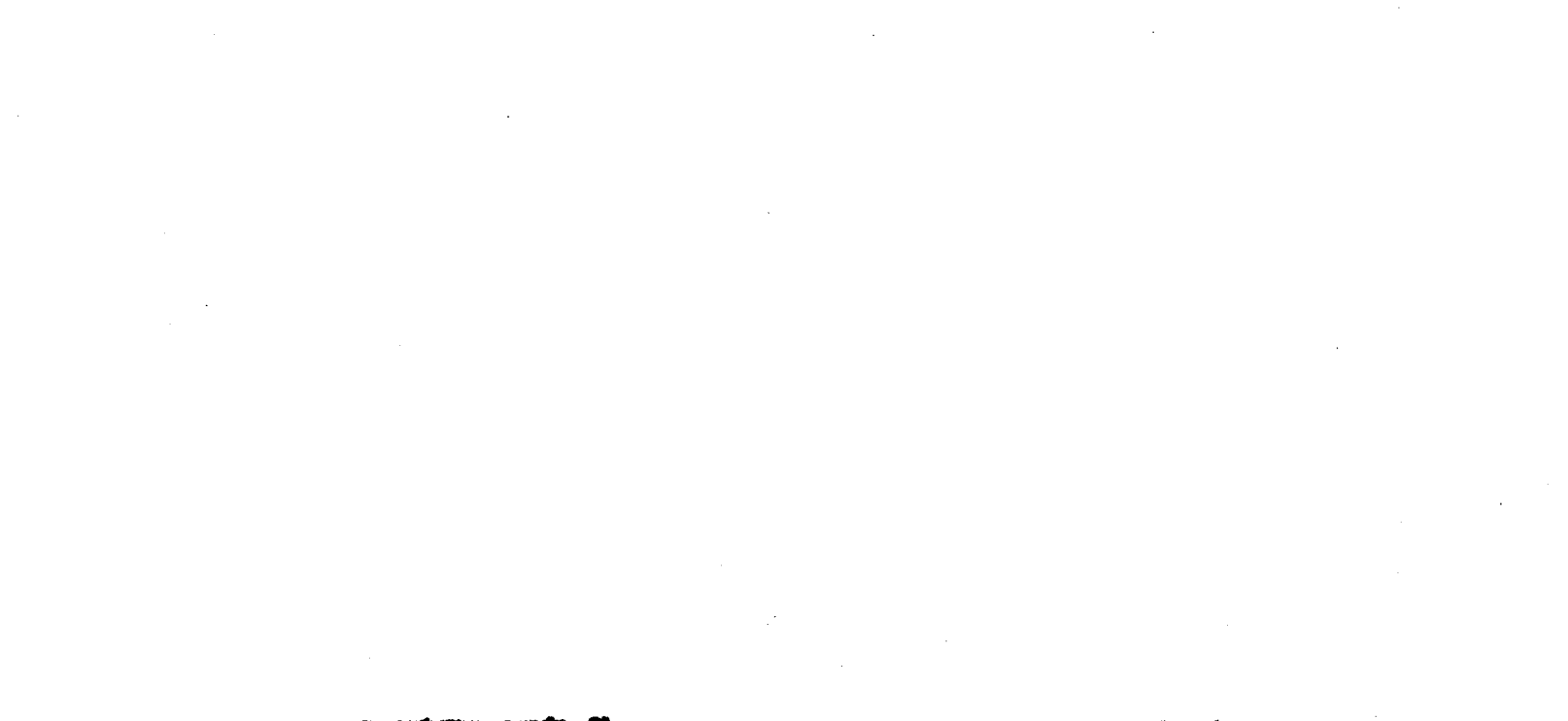
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## INTRODUCTION

The Institute for Computer Applications in Science and Engineering (ICASE) is operated at the Langley Research Center (LaRC) of NASA by the Universities Space Research Association (USRA) under a contract with the Center. USRA is a nonprofit consortium of major U. S. colleges and universities.

The Institute conducts unclassified basic research in applied mathematics, numerical analysis, and computer science in order to extend and improve problem-solving capabilities in science and engineering, particularly in aeronautics and space.

ICASE has a small permanent staff. Research is conducted primarily by visiting scientists from universities and from industry, who have resident appointments for limited periods of time, and by consultants. Members of NASA's research staff also may be residents at ICASE for limited periods.

The major categories of the current ICASE research program are:

- a. Numerical methods, with particular emphasis on the development and analysis of basic numerical algorithms;
- b. Control and parameter identification problems, with emphasis on effective numerical methods;
- c. Computational problems in engineering and the physical sciences, particularly fluid dynamics, acoustics, and structural analysis;
- d. Computer systems and software, especially vector and parallel computers.

ICASE reports are considered to be primarily preprints of manuscripts that have been submitted to appropriate research journals or that are to appear in conference proceedings. A list of these reports for the period April 1, 1985, through October 2, 1985, is given in the Reports and Abstracts section which follows a brief description of the research in progress.

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## RESEARCH IN PROGRESS

Saul Abarbanel

Together with D. Gottlieb, research continued on the question of "information content" in spectral calculations. Discontinuous solutions of hyperbolic partial differential equations have very strong numerical oscillations when computed with the aid of high-accuracy schemes such as the spectral method. It was shown that the correct piece-wise smooth solution with a well-defined discontinuity can be recovered from the oscillatory spectral solver. A different approach was also proposed by D. Gottlieb and E. Tadmor. An ICASE report entitled "Spectral Methods for Discontinuous Problems" summarizes both approaches.

The question of the convergence rate to steady state and its dependence on the mesh size was investigated. This is still ongoing research. One unexpected result concerns the use of the Douglass-Gunn AF scheme to solve the diffusion equation. If one applies the algorithm with the appropriate optimal time step in the two-dimensional case, the number of iterations necessary to reduce the residual to a given desired level is inversely proportional to the mesh-size, under the assumption of uniform mesh. In the three-dimensional case, however, the behavior is different, and asymptotically ( $\Delta x \ll 1$ ) one gets

$$n \sim (\Delta x)^{-4/3}$$

instead of  $n \sim (\Delta x)^{-1}$  as in the two-dimensional case. The importance of such investigations lies in the ability to predict code behavior for the fine-meshes which the new supercomputers will allow.

Finally, there is work in progress, with A. Bayliss and L. Lustman, on finding non-reflecting downstream boundary conditions for the Navier-Stokes equations. The analysis was done for the long-wave limit in the x-direction. We have already identified the lowest eigenfrequencies. It is hoped that in the near future boundary conditions will be derived and incorporated in working Navier-Stokes codes.

### **H. Thomas Banks, James M. Crowley, and I. Gary Rosen**

Our efforts have continued on numerical methods for the estimation of spatially dependent parameters in models for the transverse vibration of flexible beams with tip mass or tip body. We have developed and tested several different spline-based schemes based on a variational formulation. Certain phenomena regarding the inability to estimate the stiffness or damping near the free end have been observed to varying degrees in all the schemes. A number of fundamental questions in this connection are now being investigated.

### **H. Thomas Banks and Kazufumi Ito**

Efforts on the computation of feedback controls via algebraic and Chandrasekhar equations are progressing nicely. Preliminary calculations with tau-Legendre approximation schemes are quite promising for simple structures (e.g., a uniform cantilevered Euler-Bernoulli beam with viscoelastic damping). We are currently considering use of our ideas with more complex structures including those in which joint friction will play a significant role.

### **Alvin Bayliss**

Work with L. Maestrello (LaRC), P. Parikh (Vigyan Reserach Associates, Inc.), and E. Turkel continues on simulating active control using the compressible Navier-Stokes equations. We are using a fourth-order accurate method to model the problem. We recently extended the analysis to a curved surface to study the effect of pressure gradient on stability and on active surface heating and cooling. The results obtained so far are encouraging in that large changes in the flow can be imparted using relatively less power as compared to passive control methods. Some of the results are presented in the following reports: 1) AIAA Paper 85-1694, 2) NASA/ICASE Workshop on Stability of Time Dependent Flows, and 3) SAE Paper No. 851856.

**Shahid H. Bokhari**

Research is being carried out on several fronts within the field of parallel processing and distributed computing. A dynamic programming approach to the solution of distributing a chain-like task over a ring of processors developed last year has been found to have wide applications in the field of signal processing and scene analysis. It has now been extended to solve the problem of load balancing in a single-host, multiple-satellite computer system. The problem of optimally dissecting a non-uniform planar domain, generated by earlier research done in collaboration with M. Berger (New York University) (see below), has been attacked and an efficient solution found. Work on a multiprocessor algorithm for bin packing on the Argonne HEP will be transferred to the Langley FLEX machine.

**Shahid H. Bokhari and Marsha Berger**

A paper describing our preliminary work on a binary partitioning technique for rectangular domains was presented at the 1985 International Conference on Parallel Processing. We have completed a detailed analysis of this partitioning technique for hypercubes and are currently writing up our results. These provide an interesting comparison of the relative performance of meshes and hypercubes.

**Shahid H. Bokhari and M. Ashraf Iqbal**

The mapping problem for graphs does not as yet have a satisfactory solution in general. The importance of this problem is increasingly becoming obvious to researchers and practitioners in the field of parallel processing as more and more multiprocessor systems become available. Our current efforts are in the direction of finding nearly optimal solutions to this problem for binary tree structured problems. A report describing our results is in preparation.

### **Dennis W. Brewer**

Research is continuing on parameter estimation problems associated with linear evolution equations in infinite-dimensional spaces. A general algorithm based on quasi-linearization has been established along with its local convergence properties. The algorithm has been numerically tested on linear delay-differential equations. Numerical experiments indicate that the method converges rapidly when used to identify two unknown delays together with two or three unknown coefficients using simulated data. Future research will involve continuing numerical experimentation and improvements in the theory to accommodate a wider class of problems.

### **Dennis W. Brewer, J. Steven Gibson, and I. Gary Rosen**

We are continuing our efforts to develop robust software routines for identifying parameters in robotic manipulators. The programs use numerical integration of nonlinear differential equation models and nonlinear optimization algorithms. This work is in conjunction with J. Pennington (LaRC) and F. Harrison (LaRC) who have provided experimental data. Our previous research indicates a need to model the integrated electro-mechanical system to reduce parameter sensitivity. We plan to obtain data and test models which include coupled physical and actuator dynamics. In addition, input optimization should be a fruitful area for future research.

### **Janice Cuny, Piyush Mehrotra, Robert Noonan, and John Van Rosendale**

To facilitate the process of program transformation we have been designing a language called E-BLAZE. E-BLAZE is a super-set of BLAZE, a new programming language discussed elsewhere, in the sense that it extends BLAZE with the concepts of processes, semaphore protected variables, and so forth. The language E-BLAZE thus acts as a virtual machine to which BLAZE programs can be transformed. E-BLAZE also helps in the portability of BLAZE across

architectures, since E-BLAZE can be ported without reimplementing the transformations.

BLAZE is being targeted at several commercially available multiprocessor architectures. A wide variety of processors are used as individual nodes in such machines ranging from microprocessors, such as National Semiconductor's 32032 and Motorola's 68020, to mini-computers such as the VAX. We have been studying methods for implementing BLAZE on such processors, and are implementing a Graham-Glanville-Ganapathy code generator, in which a parser generator is used to produce object code. The use of an automatic parser generator makes it easy to modify the code generator for new instruction sets, and also simplifies the problem of producing high quality object code.

#### **Stephen F. Davis**

We are continuing to study simplified formulations of total variation diminishing (TVD) finite difference schemes for the solution of systems of hyperbolic partial differential equations. In particular, we have examined the performance of the TVD Lax-Wendroff scheme first reported in ICASE Report No. 84-20. An analysis of this method shows that, when it is applied to systems, a stability condition more restrictive than the usual CFL condition must be satisfied if the scheme is to remain TVD. A paper is in preparation which reports these results and examines possible ways to eliminate this extra stability restriction.

The TVD Lax-Wendroff scheme mentioned above was derived by adding a nonlinear artificial viscosity to the Lax-Wendroff method. During the reporting period we have derived similar nonlinear artificial viscosity terms for use with other popular explicit and implicit central difference schemes. Many of these methods are free from the additional stability restrictions reported above. Thus far only preliminary computations have been performed with these schemes but more work will follow.

The TVD Lax-Wendroff method has been implemented in a compressible Navier-Stokes code by David Rudy (LARC). At present the interaction between the

numerical dissipation in the scheme and the physical dissipation in the equations has caused a loss of accuracy in some computed solutions. The overall results have been encouraging so we are working together to resolve these problems.

Another method used to generate TVD schemes is the second-order Godunov method first proposed by Van Leer. Currently, we are working to simplify this scheme by substituting an approximate solution to the Riemann problem for the exact solution which is currently in use. Thus far, we have examined two simple approximate Riemann solutions which are easy to compute and which are consistent with the entropy condition across expansion waves. If the first of these approximate Riemann solutions is used, the resulting scheme is a central difference scheme. The other approximate Riemann solution creates a very simple upwinded scheme. Both schemes have performed quite well in preliminary numerical tests. A paper on this work is currently in preparation.

#### **Pravir Dutt**

In joint work with P. Drummond (LaRC), stable boundary conditions for the Navier-Stokes equations are being tested on a number of realistic flow problems. A novel feature of these boundary conditions is that they guarantee entropy boundedness for the solution to the Navier-Stokes equations.

Work is proceeding with S. Ta'asan on a multigrid-based algorithm for solving parameter estimation problems. The problem involves solving for an unknown coefficient in an elliptic boundary value problem where the solution itself is known.

#### **Pravir Dutt and S. I Hariharan**

This joint work will focus on questions related to absorbing boundary conditions for model problems arising from linear acoustic wave propagation problems. Approximation properties of resulting symbols of the pseudo-

differential operators will be studied. Results will be used to construct absorbing boundary conditions and their well-posedness will be investigated through Kreiss analysis. Numerical experiments are planned.

### **Stefan Feyock**

Work has continued on the integration of deductive capabilities into a relational database management system. The approach ultimately chosen was to create an interface between a Pascal-based Prolog implementation and the RIM database management system available at NASA/LRC. This interface was realized by adding a new built-in predicate, escape, to Prolog. escape allows communication between Prolog programs and arbitrary user-provided Pascal procedures, thus allowing the addition of any desired new capability to Prolog. Since a Pascal-based front-end procedure for RIM had been implemented earlier, the escape predicate allowed the integration of RIM into Prolog in a manner that makes RIM relations indistinguishable from Prolog assertions (unit clauses). Experiments with applications of the resulting deductive database are in progress.

### **Dennis Gannon, Piyush Mehrotra, and John Van Rosendale**

We are presently investigating the issue of parallel run-time environments. Our first target architectures are shared memory machines such as the FLEX/32 and the Alliant multiprocessor. In the first phase we are looking at schemes in which one processor acts as the "master" while the rest are its "slaves." This is one of the easiest schemes to implement and allows us to exploit "loop" level parallelism. The issues involved in automatically utilizing procedure level parallelism are more subtle and are being investigated.

Our work on program transformations for automatic extraction of parallelism, is similar to work being done by Kuck and colleagues at Illinois,

by Kennedy and colleagues at Rice University, and by Allen and others at IBM. The principal difference here is that our starting point is BLAZE, rather than Fortran or another conventional language. This dramatically simplifies extraction of parallelism, since BLAZE makes fine grained parallelism explicit and uses applicative procedure calls which obviate the need for inter-procedural analysis.

The extraction of parallelism requires an analysis of the data and control dependencies of programs. In the first phase of the project we classified some of the transformations that could be performed to convert sequential "for" loops into parallel "forall" loops. Many loops cannot be transformed into "forall" loops, but it may still be possible to transform them into pipelined or systolic structures. We are presently investigating transformations of this type.

**Dennis Gannon, Chuck Koebel, Mala Mehrotra, Piyush Mehrotra, and Kevin Miller**

The goal of the BLAZE project is to take programs having sequential control flow and automatically compile them for execution on multiprocessor architectures. Though this is an attractive idea, there are many subtle difficulties involved in doing it well, and considerable research remains to be done. An important interim step is the construction of a programming environment in which one can observe and influence the sequence of transformations carried out by the BLAZE compiler. With such an environment, one would have a sequence of "windows" on the compilation process.

We are presently constructing such a programming environment to run on VAXes and Apollos. This environment will represent programs, data dependencies, etc. graphically, and allow the user to modify the compilation process. At the moment, there is a working compiler for a BLAZE subset running on a VAX, and the language constructs not yet implemented are gradually being added. An interactive Apollo based cross-compiler for the Flex 32, and Alliant multiprocessors is in progress.



## James F. Geer

Work has begun using slender body theory to model a fully three-dimensional subsonic wing with a simple planform (e.g., a circle or an ellipse), with special attention being given to the sharp wing tips. The problem of determining exactly where and why vorticity is generated along certain portions of the wing, as well as the interaction of the vortex filaments downstream, is being considered in detail. This work is being done in collaboration with Chen-Huei Liu (LaRC) and L. Ting (New York University).

Slender body theory has been used to derive some approximate analytical solutions to the electromagnetic field problem about some simple geometrical shapes. These shapes include a slender body of revolution (to model the fuselage of an aircraft) and a two-dimensional airfoil. The goal of the investigation is to help predict the electromagnetic fields inside an aircraft which is either struck by lightning or experiences a nearby strike. The lowest order electromagnetic resonances (eigenvalues) and corresponding mode shapes (eigenfunctions) for perfectly conducting or dielectric slender bodies of revolution have been determined. These results will eventually be used to construct the time history (transient) response of a body excited by an impulsive plane wave. This work was motivated by several discussions with F. Pitts (LaRC).

A study of the reduced basis method (a semi-numerical, semi-analytical method which has been used to solve a variety of nonlinear boundary value problems in elasticity) is continuing to determine how the method might be applied to some fluid dynamic and scattering problems. Several model problems are being studied both to understand the method better and to determine its applicability. At present, these model problems include some two-point boundary value problems with boundary layers, some self-excited nonlinear oscillations, some simple exterior scattering problems, and some potential flow problems involving a slender body. The is work is being done with C. Anderson (College of William and Mary).

The method of multiple time scales has been implemented using MACSYMA and applied to the problem of determining the transient responses of the van der Pol and Duffing oscillators when the applied force consists of a sum

of periodic terms with different frequencies. The conditions under which the system will experience frequency entrainment have been investigated. The results have been extended to more general oscillators; in particular, oscillators for which both the damping and restoring terms are polynomial functions of their arguments.

### **Chester E. Grosch**

A series of calculations (in collaboration with T. Gatski, LaRC) has been initiated whose purpose is to examine the receptivity of the flat plate boundary layer to oscillations in the free stream.

A modification of the two-dimensional Navier-Stokes code of Gatski, Grosch, and Rose has been used to calculate the impulsive start-up of a slender elliptic cylinder. The objective of this work is to study the time evolution of the flow past this slender, blunt-nosed body--particularly the development in time of the separation region at the rear of the body, as a function of slenderness ratio and Reynolds number. An initial set of calculations for an angle of attack of zero, slenderness ratio of one half, and Reynolds numbers of  $10^2$ ,  $10^3$ , and  $10^4$  has been completed. These are not being written up.

Finally, in collaboration with T. Gatski (LaRC) and M. Rose, a three-dimensional Navier-Stokes code in vorticity and velocity variables using compact schemes has been developed and is now being tested against several analytic solutions.

### **Philip Hall**

The instability of boundary layers to upper and lower branch stationary disturbances has been investigated (Hall, 1985, ICASE Report No. 85-40, "An Asymptotic Investigation of the Stationary Modes of Instability of the Boundary Layer on a Rotating Disc"). The dependence of the wave angle and

wavenumber on the Reynolds number has been found. An investigation of Taylor-Görtler instabilities in interactive boundary layer flows has been completed (Hall, 1985, ICASE Report No. 85-47, "Taylor-Görtler Instabilities of Tollmien-Schlichting Waves and Other Flows Governed by the Interactive Boundary Layer Equations"). As an example it was shown that two-dimensional Tollmien-Schlichting waves are centrifugally unstable in the presence of either convex or concave curvature. The instability of some time-periodic and spatially-periodic boundary layer flows has been discussed in Hall (ICASE Report No. 85-46, "Instability of Time-Periodic Flows"). Current work is concerned with the interaction of Tollmien-Schlichting waves and crossflow vortices. With M. Malik (High Technology Corporation) the instability of compressible boundary layers is being investigated.

#### **Subramaniya I. Hariharan**

Studies on nonlinear acoustic wave propagation in the atmosphere are being continued. In the first part of the study we introduced a model in which the nonlinear problem can be decomposed into a sequence of linear problems. The well-posedness of these problems was investigated. Currently, discrete versions of the above problems are under consideration. As an interesting case, physical as well as mathematical, the numerical approximations of pulse sources are being considered. Moreover, the dispersion relations that were obtained from the linear problems are being considered to derive appropriate farfield boundary conditions that are suitable for numerical computations.

Currently, wave envelope techniques to accelerate convergence of electromagnetic wave guide problems are being completed. The wave guide can contain a variable index of refraction. In particular, it can be arbitrary. Special attention is given to the situation of multi-mode propagation, which is known to be hard to compute. This work is being done in collaboration with S. I. Sudharsanan (University of Tennessee Space Institute).

Influence of acoustic waves on compressible viscous flows past blunt bodies are being considered. In particular, flow past an elliptic cylinder

will be undertaken. This study is planned on a long range basis. The first part of the study will be to write a compressible Navier-Stokes code. In this code, recently available accurate farfield boundary conditions will be used to cut the cost of computation. Also, this will allow one to resolve the boundary layer with a reasonable computational effort. The boundary layer will be the key point of concentration. In the second stage, acoustic disturbances will be introduced in the flow, and the Navier-Stokes solution will be obtained using the above code for the disturbed field. From the difference of the solutions, the influence of acoustics will be analyzed.

#### **M. Yousuff Hussaini**

The program of research in hydrodynamic stability and transition to turbulence is continuing. Relative advantages of LFC techniques such as heating, suction, and pressure gradient are being investigated. Preliminary results are reported in the paper AIAA 85-1698. A refined simulation of the Rayleigh-Benard convection problem was carried out. The data are being analyzed. One of the highlights of the simulation is the prediction of the Nusselt number closest to the experimentally measured value. Also, the axisymmetric configurations of finite length Taylor-Couette flow is being studied with a view to verifying the relevant bifurcation theories.

The basic study on turbulence alteration due to shock motion is being continued using model problems. The eddy shocklets observed in high speed free shear layers are modelled within the framework two-dimensional compressible Navier-Stokes equations. A subsonically convecting eddy is injected into a supersonic stream. The subsequent shocklet formation and eddy deformation is simulated with a view to unravel physical mechanisms that would possibly explain the decrease in entrainment rate at high Mach numbers. Some results of these simulations were reported at the International Union of Theoretical and Applied Mechanics (IUTAM) Symposium held at Palaiseau, France, during the week of September 9, 1985.

The actual physical mechanisms through which the external disturbance environment triggers instability and transition to turbulence in a boundary layer are not well understood. In order to throw some light on this so-called receptivity problem, we intend to construct an accurate and efficient numerical method for solving the three-dimensional compressible Navier-Stokes equations relevant to the initial-boundary value problem corresponding to certain physical experiments. The initial algorithm will handle Cartesian geometry, and then with subsequent modifications, the algorithm will be able to handle conical and other configurations.

We plan to study the phenomenological aspects of quasi-steady three-dimensional flow past a circular cylinder standing normal to a flat plate. The vortical structures are known to be sensitive to the geometry of cylinder-plate juncture as well as the Mach number and Reynolds number of mainstream. This will be the focus of our theoretical study based on the numerical solution of the unsteady three-dimensional compressible Navier-Stokes equations.

This program of research is being carried out in collaboration with L. Balasubramanian, G. Erlebacher (LaRC), C. L. Streett (LaRC), and T. A. Zang (LaRC).

### **Moshe Israeli**

Theoretical and numerical investigation of the Parabolized Navier-Stokes equations is in progress for the steady state compressible two-dimensional case and for incompressible three-dimensional steady flow. Efficient iterative algorithms are developed by modifying the pressure terms in the streamwise momentum equation. New results include surface stream lines for a spheroid at an angle of attack. This research is being done in collaboration with M. Rosenfeld (Technion Israel Institute of Technology) and M. Salas, (LaRC).

With E. Tadmor and M. Y. Hussaini, the application of spectral methods for problems with thin boundary or internal layers was considered. It was found

that the resolution of such methods decreases exponentially with the "grid Reynolds number." It follows that in the presence of thin layers a prohibitively large number of points is required for adequate resolution. Using a class of smooth stretching transformations we are able to obtain a considerable improvement in resolution.

The applicability to parallel computation of a new two-grid explicit/implicit solution technique for parabolic partial differential equations is under investigation with J. Saltz. The scheme is found to have low overhead and allows for considerable speed up. Several parallel architectures are being analyzed.

Nonlinear acceleration methods are applied point by point to the sequence obtained from the time marching solution of partial differential equations approaching a steady state. The resulting algorithm is analyzed theoretically for the solution of elliptic equations. It is shown that an optimal time step results in an extremely fast convergence rate. Numerical experiments for the approximate factorization method support these conclusions. Suitability of the algorithm for computational fluid dynamics codes is currently under investigation

#### **Kazufumi Ito and Robert K. Powers**

Efforts are continuing in the application of Chandrasekhar-type algorithms to infinite dimensional linear quadratic regulator (LQR) problems that have unbounded inputs and outputs (i.e., boundary control and observation). Approximation of the associated gain operators via the Chandrasekhar equations has been shown to be more computationally efficient than approximation via the Riccati equation for many problems with bounded inputs and outputs. The features of the Chandrasekhar equations that make them computationally efficient are present in many problems involving boundary controls and observations. Numerical techniques for solving such problems are being sought.

**Harry Jordan**

Work is in progress to transport a shared memory multiprocessor programming system to the FLEX/32 computer and to extend its applicability to a wider class of parallel algorithms. The system, known as the force, was originally implemented on the HEP pipelined multiprocessor and applied to some fluid dynamics computations. The FLEX/32 system was studied and initial versions of the macros comprising the system were written. Some of these were tested in a Concurrent C form with the aid of J. Panetta (Purdue University) and the Purdue FLEX/32, as the Langley machine had not yet arrived. Interesting comparisons and contrasts arose between the two multiprocessor versions of the force macros. An initial design was formulated for the extension of the force system to support algorithms parallelized on the basis of function rather than data structure.

Together with G. Alaghband (University of Colorado) the design and analysis of an algorithm for sparse L/U decomposition on a multiprocessor was pursued. The amount of parallel activity attainable by processing multiple pivot elements simultaneously was investigated for sparse matrices arising from the electronic circuit simulation area. On the basis of the information obtained, a parallel pivot selection algorithm was developed which is able to take advantage of a large amount of parallelism while controlling fill-in. Parameters of the algorithm allow parallelism to be traded for fill-in reduction in a fairly smooth manner.

**William D. Lakin**

Integrating and differentiating matrices based on one-dimensional sliding subgrids form the basis for an efficient numerical procedure for solving eigenvalue problems associated with the vibration and buckling of rotating flexible beams. Traditionally, beam configurations have provided models for studying rotating structures such as helicopter rotor blades and propeller blades.

More recently, models for rotor blades involving elastic plates have been proposed to include the effects of spanwise variations in material properties. To deal with the associated two-dimensional eigenvalue problems, the present work has developed integrating and differentiating matrices based on non-uniform rectangular grids with "near boundary" points. The eigenvalue problem for a simply-supported rectangular plate has been used as a test case. Reformulation of this problem as an integro-differential equation consistent with the boundary conditions and approximation of the operators by appropriate integrating, differentiating, and boundary-evaluation matrices has been shown to lead to a standard matrix eigenvalue problem for a "stacked" column vector. Numerical solutions of this eigenvalue problem are found to be in good agreement with exact results.

#### **Liviu Lustman**

Various iterative techniques have been studied for the solution of steady state elastic problems, as discretized by compact schemes. It appears that the most efficient are based on using together the three residuals which result from traction balance in the  $x$ ,  $y$ , and  $z$  directions respectively. These residuals can, however, be computed in parallel. Using conjugate gradient techniques, various exact solutions to simple problems have been reproduced numerically. These include linear displacement problems for layered materials and general biharmonic solutions for the isotropic case. A computational study is in progress, which aims to determine the dependence of the convergence rate and final accuracy on the two parameters used in eliminating the stresses from the basic elasticity equations. This work has been performed in collaboration with M. E. Rose and S. Ta'asan.

Joint research with D. Gottlieb and E. Tadmor has been done on spectral collocation methods applied to initial-boundary value problems for hyperbolic systems. Stability results have been obtained for Chebyshev collocation, and some other polynomial classes have been identified which also generate stable collocation methods.



Computations have been performed in order to identify optimal numerical boundary conditions for Navier-Stokes steady state problems. Following the model of S. Abarbanel and A. Bayliss, certain parameters are computed as eigenvalues of problems similar to the standard Orr-Sommerfeld equations. Preliminary Navier-Stokes calculations using these new boundary conditions indicate a substantial convergence speedup.

### **Piyush Mehrotra and John Van Rosendale**

We have recently designed a parallel programming language, BLAZE, intended for scientific computing. BLAZE is a parallel language but not a multi-tasking language. The user designs programs with sequential control flow, and the compiler transforms the program for multiprocessor execution.

Our language resembles conventional languages, such as Pascal and C, though it is intended for scientific computing and thus contains extensive array manipulation facilities. The most fundamental difference between this language and conventional languages is that BLAZE uses applicative procedure calls. That is, procedures behave as "functions" which have input and output parameters passed by value, but have no side-effects. With such semantically clean parameter passing, data flow analysis is quite trivial, and it is relatively easy for compilers to automatically extract coarse-grained parallelism. BLAZE also contains several constructs, such as "forall" loops and array arithmetic, allowing programmers to easily express fine-grained or "vector" parallelism.

Recent work has focused both on the implementation of this language on a variety of parallel computers, and on a sequence of potential extensions which would allow easy expression of more kinds of parallelism. We are also studying inclusion of a number of important features from conventional languages, including separate compilation, exception handlers, and abstract data types.

**Vijay K. Naik and David M. Nicol**

A parallel simulation test-bed system is under design. This system will simulate the behavior of message passing multi-processor systems in a parallel fashion. Potential target machines for this test-bed include the FLEX/32 and the Intel Hyper-Cube. This simulation system will be a useful tool for studying massively parallel algorithms on relatively fewer number of processors; it will also provide a test-bed for experiments with algorithm partitioning schemes and dynamic load balancing policies for both the simulation itself and for the simulated massively parallel systems. In addition, this simulator will be used for studying the comparative effectiveness of different synchronization schemes inherent to parallel simulations.

**Vijay K. Naik and Joel H. Saltz**

There are numerous problems involving time dependent partial differential equations for which obtaining a relatively accurate solution can be an expensive, time consuming process. In many algorithms for the solution of such time dependent problems, it is necessary to solve a sequence of linear equations involving the same coefficient matrix but a different "right-hand side." The "right-hand sides" of equations corresponding to the consecutive steps are dependent on the solutions of the equations corresponding to the earlier time steps in the sequence.

Our research is aimed at discovering how to solve these problems efficiently on multiprocessors. One of the factors that reduces the efficiency of multi-processor algorithms and limits the number of processors that may be usefully employed is the amount and the timing of communication that must take place between problem partitions that run on different processors. Iterative algorithms that involve partitioning the domain of the partial differential equation and with each partition sweeping over several time steps reduce synchronization and convergence checking requirements and allow overlap of computation and communication. The performance implications

of this communication and computation overlap vary with the architecture of the multi-processor system. Similarly the hardware requirements vary for various communication and computation overlap strategies. These issues are currently being analyzed. Performance models are being developed for some existing MIMD architectures as well as for some hypothetical systems. The results from the analytical models are compared with those obtained by actually implementing these schemes on existing MIMD machines such as the FLEX/32 and the Intel Hyper-cube.

### **Vijay K. Naik and Shlomo Ta'asan**

Algorithms based on multigrid techniques are known to be among the most efficient methods for solving partial differential equations. On sequential machines, a wide class of problems discretized on a grid with  $n$  points requires only  $O(n)$  arithmetic operations to obtain a solution to within the truncation error of the discretization. This makes the multigrid methods optimal on the sequential machines. This optimal property, together with the fact that many aspects of the multigrid algorithms are highly parallelizable, makes these methods attractive for implementation on multi-processor systems. Several researchers have studied the effects of parallelizing the intra-grid and inter-grid operations. Some researchers have proposed special purpose architectures which allow one to map some important problems directly onto the hardware and thus reduce the communication delay effects. But none of these studies has conclusively shown that the optimality observed on the sequential machines is conserved in time and the number of processors needed when these methods are implemented on multiprocessors, nor is there any clear understanding about the communication and the synchronization costs involved.

The work undertaken here is to explore the above mentioned questions further for shared and non-shared memory architectures. The effort is aimed at studying the effects of various communication strategies and also at understanding the effects of various implementations on the convergence rates. We are also studying the advantages and disadvantages of using a large number

of simple processors and those of using a small number of powerful processors. In addition to these studies, investigation is currently under way towards the development of new algorithms which possess some of the numerical properties of multigrid methods, but do not require tight synchronizations. These studies will be carried out on the currently available MIMD machines such as the Intel Hyper-cube and the FLEX/32.

### **Vijay K. Naik and John Van Rosendale**

An examination of numerical programs indicates that most of the available parallelism is concentrated at the loop level, rather than at the procedure level. One of the recent innovations in vector computers is "scatter-gather" hardware, which allows general permutations of data, thereby broadening the class of loops which can be performed efficiently. But for many types of loops the ability to permute data is not sufficient. For example, the computation of the product of a sparse matrix and a vector cannot be done easily on a vector computer, even if scatter-gather hardware is available.

A natural generalization of permutation is the "replace-add" or "fetch-add" operation of the NYU Ultracomputer. This operation allows many processors in a multiprocessor system to access and update semaphores in parallel. Many numerical problems, including sparse matrix problems, particle-in-cell plasma simulations, and galaxy simulations require exactly this type of operation. But "replace-add" hardware is probably not the complete answer since, for one thing, the size of problem which can be solved is limited by the size of the "replace-add" network available. As an alternative, we are studying the use of single-stage multi-microprocessor networks which can be used to emulate a "replace-add" network of arbitrary size. Simulation results obtained indicate that this approach reduces or eliminates load balancing problems and that the use of a single-stage network used in this way may be more attractive than the use of Log-stage networks, such as the Omega network. Modelling and performance analysis of such systems is currently under way.

**Michele Napolitano**

An incremental multigrid method for solving the vorticity-stream function Navier-Stokes equations has been modified to extend its applicability to non-uniform grids. A computer code has been developed for solving viscous steady flow past a backward facing step inside a channel, using an alternate-line-Gauss-Seidel relaxation method. The program employs both a multigrid method and an extrapolation technique, based on minimal residual concepts, to achieve fast convergence to steady state. A one-dimensional multigrid method has been devised to solve viscous flows having a dominant flow-direction and has been successfully applied to compute high Reynolds number flow in a diffuser. Most of this work has been performed in cooperation with J. Morrison (VPI & SU) and will appear in an ICASE report.

**David M. Nicol and Joel H. Saltz**

We are considering parallel computations where the workload of each processor as a function of time may be modeled as a discrete time birth-death process, and where the processors fully synchronize at each time step of these processes. Specific problems in which the workload may be viewed in this way are identified. The execution time of a synchronization step can be calculated by identifying the processor with maximal workload at that step. Execution speedup can be achieved by balancing the total workload among processors; however, the act of balancing exacts a delay on the overall execution time. This execution time delay on a message passing architecture arises from the need to calculate a remapping of a problem and from the need to transmit required data to new processors. In shared memory architectures with caches or local memories associated with each processor, data must be moved from the cache or local memory of one processor to another when processes requiring given data are run consecutively on various processors.

We have formulated the problem of deciding to load balance as a Markov decision process. In theory, it is then possible to calculate the load balancing decision policy which minimizes the overall expected execution time

of the computation. Unfortunately, determining this policy is exponentially complex in the number of processors. Moreover a knowledge of all transition probabilities of all of the Markov processes is required for the full implementation of this policy. We are thus led to consider approximations to the optimal decision policy.

We restrict our attention to the class of policies that balances load when various measures of throughput have fallen below a given point. The decay in performance observed following a load balance is modelled analytically. An expression is obtained for the overall rate of performing work as a function of the performance threshold at which one load balances. The efficacy of the different throughput measures is compared by the use of a simulated load consisting of the discrete birth-death Markov processes.

#### **Robert E. Noonan**

Research continues on applying table-driven code generation techniques to parallel architecture computers. A code generator is viewed as a three-stage process. In the first stage, the intermediate code is transformed from a machine-independent language to one involving machine dependencies. As part of this process, some operations are optimized while others are merely mapped to equivalent but computationally simpler operations. In the second stage, machine (or assembly) code is actually generated for the target machine using an LR parser to recognize certain sequences in the intermediate code language. In the final stage, the machine code is optimized by a peephole optimizer.

All three stages exist as Pascal programs; however, the second and third stages are not as well integrated as the first two. Currently, separate specifications are used for each stage. Research continues on developing a single specification from which the tables for all three stages would be derived.

Additional research consists of using the second stage of the code generation process in the compiler for the Blaze language. In this case, the intermediate code form consists of indirect triples. Research has centered on

two subprograms. The first is producing fairly optimized (local) code in the absence of any global flow information. The second is the investigation of various register allocation policies.

### **Merrell L. Patrick**

Computing systems of the future for large scale scientific and engineering computations will consist of many processors and memories working in parallel to solve a single problem. Efficient use and ease of use of these future systems are two basic problems facing potential users. The development of new parallel algorithms, parallel execution time models which predict the performance of the algorithms on different parallel architectures, and parallel programming environments for expressing the algorithms are essential for progress toward the solution of these problems.

In collaboration with D. Reed (University of Illinois) the applicability of static data flow architectures to the iterative solution of sparse linear systems of equations was investigated. An analytic performance model of a static data flow computation was developed. The model included both spatial parallelism, concurrent execution in multiple PEs, and pipelining, the streaming of data from array memories through the PEs. The performance model was used to analyze the performance of a row partitioned, iterative algorithm for solving sparse linear systems of algebraic equations. Based on the results of this analysis, design parameters for the static data flow architecture as a function of matrix sparsity and dimension are proposed. The impact of other partitionings of the linear systems on performance is under investigation.

Work with T. Pratt (University of Virginia) and H. Jordan (University of Colorado) is continuing on trying to define the essential ingredients of parallel programming languages for scientific computations. Different programming paradigms are being considered with special attention given to parallel programming of the FLEX/32 parallel processing system at NASA Langley.

A new study was begun with L. Adams (UCLA) and D. Reed (University of Illinois) to determine effects of different problem domain partitionings, given a discretization stencil, on the communication to computation ratios in a multiprocessor system.

### **Robert K. Powers**

Active controls for aeroelastic systems often result in increased life and better flutter characteristics of aircraft. Paramount in current models for active control of flutter is the approximation of the so-called Wagner function. It has been shown that the Wagner function is related to the output of a system governed by a functional differential equation. Joint work with J. Burns (VPI & SU) is being conducted in which the hereditary nature of the Wagner function is being modeled in terms of delay-differential equations. The controls are obtained via a linear quadratic regulator approach (LQR).

Research is underway with T. Banks (Brown University) and J. Juang (LaRC) to estimate parameters in flexible beams. In particular, efforts are being made to estimate the damping of flexible beams due to air resistance. The presence of the damping term produces nonlinearities in the model equations. Spline-based types of finite elements are being used for approximations.

Research is also continuous with K. Ito (Brown University) on the application of Chandrasekhar-type algorithms to infinite dimensional LQR problems in which the input and output operators are unbounded.

### **Terrence W. Pratt**

The PISCES parallel programming environment allows the scientific programmer to write parallel programs that are intended to run on various parallel architectures. Programming is in PISCES Fortran (an extension of Fortran 77) under the Unix operating system. Several "granularities" of parallel operations are provided.



The PISCES 1 environment has been implemented on the ICASE VAX 750 and on a network of Apollo Domain workstations at the University of Virginia. In PISCES 1, a program is organized in clusters of tasks that communicate by passing messages.

The PISCES 2 environment is being designed and implemented for the Flexible Corporation FLEX/32 at NASA Langley. PISCES 2 extends PISCES 1 to include the 'force' constructs developed by H. Jordan (University of Colorado) which allow the programmer to make effective use of the shared memory of the FLEX/32. PISCES 2 also allows the programmer to control the mapping from PISCES clusters to the hardware processors.

#### **Milton E. Rose**

In joint work with T. Gatski (LaRC) and C. Grosch (ODU), a finite difference method to solve the time dependent incompressible three-dimensional Navier-Stokes equations is being studied. The underlying construction employs separate local solution bases for the velocity and vorticity fields.

With L. Lustman and S. Ta'asan compact finite difference equations are being studied to treat the equilibrium of an n-ply rectangular plate. Simple iterative techniques are being examined with the purpose of laying the groundwork for developing multigrid methods.

#### **Joel Saltz and Hillel Tal-Ezer**

Methods of obtaining rapid solutions to time dependent problems utilizing spectral methods in space and finite differences in time are being explored. Methods of implementing these algorithms on an intel hypercube multiprocessor are being evaluated. We have shown that Richardson extrapolation leads to markedly improved efficiency when it is desirable to match the highly accurate spectral method in space with a similarly accurate method for integrating in time. The use of Richardson extrapolation allows for the use of several

loosely coupled machines (in our implementation, themselves multiprocessors) in the solution of the problem.

### **Ke-Gang Shih**

A model nonlinear eigenvalue problem of a singular ordinary differential equation is under study. The goal is to see if we will get the so-called "numerically irrelevant solutions," and if so, how an incorporation of nodal properties of solutions may help to avoid them. The patch bases method of Rose (1984) is used. The numerical results of the linearized eigenvalue problem show that it is a second-order method.

A three-dimensional problem of a composite cylindrical shell is also under study, jointly with M. Rose and L. Lustman, to assess the efficiency of a compact finite element method proposed by Rose (1985) applied to such a problem.

### **Shlomo Ta'asan**

A multigrid treatment of compact finite elements is being studied. Experiments with the Poisson equation and the elasticity equations have been made for different types of boundary conditions. Examination of these methods for some model problems which are of physical interest is being done.

Multigrid treatment of highly oscillatory problems, such as exterior problems in acoustics, is the subject of another study. The main idea here is to use a ray representation of the solution (similar to Geometrical Optics) on coarse grids, which allows a natural treatment of radiation boundary conditions as well as other advantages. This work is in collaboration with A. Brandt (Weizmann Institute).

Another direction of multigrid development is for system identification. Here the problem is to estimate certain coefficients in an elliptic equation for which a right-hand side and a solution are given. Estimation of the coefficient is needed under some minimization constraint.

### Eitan Tadmor

Together with M. Hussaini and M. Israeli (Princeton University), we have considered the application of spectral methods for problems with thin boundary and interior layers. We have verified that the resolution of such methods increases exponentially as a function of the 'grid Reynolds number.' Using scale transformations, we change the effective Reynolds number thus obtaining an improved resolution.

We are working together with D. Gottlieb and L. Lustman on the stability analysis of spectral and pseudospectral methods for hyperbolic initial-boundary value systems. Our convenient stability criterion avoids checking the intricate coupling of the equations through the boundary conditions. Examples of stable pseudospectral codes are treated along the lines of the above stability theory.

Together with S. Abarbanel (Tel-Aviv University) and D. Gottlieb we have studied the application of spectral methods for discontinuous problems. The typical spectral numerical solution is globally oscillatory in these cases. It is shown that by pre- and post-processing such oscillatory solutions one can recover pointwise values within the normal rapidly decaying spectral accuracy.

We study finite difference and finite element schemes for discontinuous problems connected with nonlinear conservation laws. We have devised a new easily implemented nonoscillatory control differencing code which is a second-order accurate one. We have also constructed entropy conservative schemes, and have shown how these can be used as a building block for designing (possibly second-order accurate) entropy stable schemes.

**Hillel Tal-Ezer**

A numerical solution of time-dependent problems which utilizes spectral methods in space and a finite difference approach to march the solution in time results in an unbalanced scheme. It has high accuracy in space and relatively low accuracy in time. In previous ICASE reports, obtaining a spectral algorithm both in time and in space for linear problems has been discussed. Very satisfactory results have been achieved for solving Schrodinger equations (in collaboration with R. Koslov, Hebrew University, Jerusalem). The algorithm has been applied also to some geophysical problems (in collaboration with D. Koslov, Tel-Aviv University) and has proved to be a useful tool in these cases. Using this method for more complicated problems (time-dependent coefficients, source terms, nonlinear) is being studied. Another direction of the present research is the investigation of Richardson extrapolation in order to increase the accuracy in time. Implementing this approach on parallel machines is being studied in collaboration with J. Saltz.

**Eli Turkel**

Joint work is continuing with A. Bayliss (Exxon Corporate Research Laboratory), L. Maestrello (LaRC), and P. Parikh (Vigyan Research Associates, Inc.). We are interested in the stability of the time-dependent, compressible, viscous, laminar Navier-Stokes equations. Once a steady state is calculated the inflow is perturbed, and we calculate the resultant spatially growing or decaying solution. A description of the fourth-order method was given in an ICASE report and presented at the AIAA conference in Cincinnati. An ICASE report was also written on the control of these instability waves by heating and cooling. At present, we are extending the code to deal with geometries more varied than a flat plate. We are finding cases where a steady flow still exists without separation. A three-dimensional version of the code has been written and is being debugged.

Work is also continuing on preconditionings for the incompressible and low Mach compressible equations. Extensions have been made to the previous work

both in the analysis and in computations. The new preconditioning allows for an isotropic wave speed and shows that the resultant equations are still symmetrizable. One ICASE report has appeared and a second is being written. Work is progressing on a joint project with C. Swanson (LaRC) on the extension of the Crocco scheme to a Runge-Kutta scheme. Computations are being performed and an ICASE report is being prepared.

An analysis of schemes for nonuniform grids has been started. Both the stability and accuracy of finite difference and finite volume schemes are being analyzed. It is shown that one usually loses accuracy on nonalgebraically stretched meshes but that new formulas can be devised to restore the accuracy. Computations have been performed in both two and three-space dimensions. One ICASE report is being completed and a second one is being prepared.

Joint work with C. Swanson (LaRC) and V. Vatsa (LaRC) is continuing on the use of Runge-Kutta methods for the Navier-Stokes equations. Accelerations based on enthalpy damping and residual smoothing are being pursued. The three-dimensional version is now running using both a C-H topology and an O-O topology. Work has also begun with A. Kumar (LaRC) and A. Moitra (Systems and Applied Sciences Corp.) to extend the Runge-Kutta schemes to nozzle geometries.

#### **Bram van Leer**

Steady-flow problems in aerodynamics often have to be solved on strongly non-uniform grids. The inclusion of the cell dimensions in the interpolation formulas for state quantities at a cell face is not a trivial matter and, within the order of the truncation error of a scheme, is not unique. Formulas for second- and third-order upwind-biased schemes approximating the Euler equations were derived from the principle that the interpolation be exact for a purely linear and for a quadratic distribution, respectively. A series of one-dimensional linear test computations by J. Thomas (LaRC) confirmed the improvement in accuracy achieved by the new formulas. Applications to the

Low-Speed Aerodynamics Division's two-dimensional/three-dimensional Euler code is under way.

### **Robert G. Voigt**

The nature of high performance scientific computing is under study with J. Olinger (Stanford). Such computing involves many stages and disciplines: problem definition--engineering and the sciences; mathematical formulation--engineering, the sciences, and applied mathematics; discretization and algorithm formulation--numerical and algorithmic analysis; algorithm description and implementation--computer languages and systems; execution of the calculation--computer hardware; and interpretation of the results--data base management, graphics, etc. A central theme is that synergism between these phases and disciplines is necessary to produce a modern computational environment; that is, one which can be easily used, employs modern technology, exploits parallelism to a high degree, and utilizes sophisticated, efficient algorithms. Several other researchers have been asked to write on various aspects of the synergistic process, and the result is intended as a volume in the SIAM Frontiers of Applied Mathematics series.

## REPORTS AND ABSTRACTS

Davis, S. F.: *Shock capturing*. ICASE Report No. 85-25, April 26, 1985, 23 pages. To appear in Numerical Methods for Partial Differential Equations, S. I. Hariharan and T. H. Moulder (eds.), Pitman, 1986.

This chapter describes recent developments which have improved our understanding of how finite difference methods resolve discontinuous solutions to hyperbolic partial differential equations. As a result of this understanding improved shock capturing methods are currently being developed and tested. Some of these methods are described and numerical results are presented showing their performance on problems containing shocks in one and two dimensions.

We begin this discussion by defining what is meant by a conservative difference scheme and showing that conservation implies that, except in very special circumstances, shocks must be spread over at least two grid intervals. These two interval shocks are actually attained in one dimension if the shock is steady and an upwind scheme is used. By analyzing this case, we determine the reason for this excellent shock resolution and use this result to provide a mechanism for improving the resolution of two-dimensional steady shocks. Unfortunately, this same analysis shows that these results cannot be extended to shocks which move relative to the computing grid.

To deal with moving shocks and contact discontinuities we introduce total variation diminishing (TVD) finite difference schemes and flux limiters. We show that TVD schemes are not necessarily upwind, but that upwind TVD schemes perform better because they permit a wider choice of flux limiters. The advantage of non-upwind TVD schemes is that they are easy to implement. Indeed, it is possible to add an appropriately chosen artificial viscosity to a conventional scheme such as MacCormack's method and make it TVD. We conclude by presenting some theoretical results on flux limiters and some numerical computations to illustrate the theory.

Brandt, A. and S. Ta'asan: *Multigrid solutions to quasi-elliptic schemes*. ICASE Report No. 85-26, May 10, 1985, 21 pages. Progress and Supercomputing in Computational Fluid Dynamics, (E. M. Murman and S. S. Abarbanel, eds.), Birkhauser Boston, Inc., 1985, pp. 235-255.

Quasi-elliptic schemes arise from central differencing or finite element discretization of elliptic systems with odd order derivatives on non-staggered grids. They are somewhat unstable and less accurate than corresponding staggered-grid schemes. When usual multigrid solvers are applied to them, the asymptotic algebraic convergence is necessarily slow. Nevertheless, it is shown by mode analyses and numerical

experiments that the usual FMG algorithm is very efficient in solving quasi-elliptic equations to the level of truncation errors. Also, a new type of multigrid algorithm is presented, mode analyzed and tested, for which even the asymptotic algebraic convergence is fast. The essence of that algorithm is applicable to other kinds of problems, including highly indefinite ones.

Zang, T. A. and M. Y. Hussaini: *On spectral multigrid methods for the time-dependent Navier-Stokes equations*. ICASE Report No. 85-27, May 13, 1985, 24 pages. Presented at the 2nd Copper Mountain Conference on Multigrid Methods, April 1-3, 1985, Copper Mountain, CO.

A new splitting scheme is proposed for the numerical solution of the time-dependent, incompressible Navier-Stokes equations by spectral methods. A staggered grid is used for the pressure, improved intermediate boundary conditions are employed in the split step for the velocity, and spectral multigrid techniques are used for the solution of the implicit equations.

Osher, S. and E. Tadmor: *On the convergence of difference approximations to scalar conservation laws*. ICASE Report No. 85-28, May 14, 1985, 70 pages. Submitted to Math. Comp.

We present a unified treatment of explicit in time, two level, second order resolution, total variation diminishing, approximations to scalar conservation laws. The schemes are assumed only to have conservation form and incremental form. We introduce a modified flux and a viscosity coefficient and obtain results in terms of the latter. The existence of a cell entropy inequality is discussed and such an equality for all entropies is shown to imply that the scheme is an E scheme on monotone (actually more general) data, hence at most only first order accurate in general. Convergence for TVD-SOR schemes approximating convex or concave conservation laws is shown by enforcing a single discrete entropy inequality.

Mehrotra, P. and J. Van Rosendale: *The BLAZE language: A parallel language for scientific programming*. ICASE Report No. 85-29, May 15, 1985, 57 pages. Submitted to Parallel Computing.

Programming multiprocessor parallel architectures is a complex task. This paper describes a Pascal-like scientific programming language, Blaze, designed to simplify this task. Blaze contains array arithmetic, "forall"



loops, and APL-style accumulation operators, which allow natural expression of fine grained parallelism. It also employs an applicative or functional procedure invocation mechanism, which makes it easy for compilers to extract coarse grained parallelism using machine specific program restructuring. Thus Blaze should allow one to achieve highly parallel execution on multiprocessor architectures, while still providing the user with conceptually sequential control flow.

A central goal in the design of Blaze is portability across a broad range of parallel architectures. The multiple levels of parallelism present in Blaze code, in principle, allow a compiler to extract the types of parallelism appropriate for the given architecture, while neglecting the remainder. This paper describes the features of Blaze and shows how this language would be used in typical scientific programming.

Trefethen, L. N. and L. Halpern: *Well-Posedness of one-way wave equations and absorbing boundary conditions*. ICASE Report No. 85-30, June 10, 1985, 23 pages. Submitted to Math. Comp.

A one-way wave equation is a partial differential equation which, in some approximate sense, behaves like the wave equation in one direction but permits no propagation in the opposite one. The construction of such equations can be reduced to the approximation of  $\sqrt{1 - s^2}$  on  $[-1,1]$  by a rational function  $r(s) = P_m(s)/q_n(s)$ . This paper characterizes those rational functions  $r$  for which the corresponding one-way wave equation is well-posed, both as a partial differential equation and as an absorbing boundary condition for the wave equation. We find that if  $r(s)$  interpolates  $\sqrt{1 - s^2}$  at sufficiently many points in  $(-1,1)$ , then well-posedness is assured. It follows that absorbing boundary conditions based on Padé approximation are well-posed if and only if  $(m,n)$  lies in one of two distinct diagonals in the Padé table, the two proposed by Engquist and Majda. Analogous results also hold for one-way wave equations derived from Chebyshev or least-squares approximation.

Majda, G.: *A new theory for multistep discretizations of stiff ordinary differential equations: Stability with large step sizes*. ICASE Report No. 85-31, 70 pages. Submitted to Math. Comp.

In this paper we consider a large set of variable coefficient linear systems of ordinary differential equations which possess two different time scales, a slow one and a fast one. A small parameter  $\epsilon$  characterizes the stiffness of these systems. We approximate a system of o.d.e.s in this set by a general class of multistep discretizations which includes both one-leg and linear multistep methods. We determine sufficient conditions under which each solution of a multistep method is uniformly

bounded, with a bound which is independent of the stiffness of the system of o.d.e.s, when the step size resolves the slow time scale but not the fast one. We call this property stability with large step sizes.

The theory presented in this paper lets us compare properties of one-leg methods and linear multistep methods when they approximate variable coefficient systems of stiff o.d.e.s. In particular, we show that one-leg methods have better stability properties with large step sizes than their linear multistep counterparts. This observation is consistent with results obtained by Dahlquist and Lindberg [11], Nevanlinna and Liniger [32], and van Veldhuizen [41]. Our theory also allows us to relate the concept of D-stability (van Veldhuizen [41]) to the usual notions of stability and stability domains and to the propagation of errors for multistep methods which use large step sizes.

Banks, H. T.: *On a variational approach to some parameter estimation problems.* ICASE Report No. 85-32, 38 pages. Invited lecture, International Conference on Control Theory for Distributed Parameter Systems and Applications, July 9 - 14, 1984, Voran, Austria.

We consider examples (1-D seismic, large FLEXible structures, bioturbation, nonlinear population dispersal) in which a variational setting can provide a convenient framework for convergence and stability arguments in parameter estimation problems.

Hariharan, S. I.: *Absorbing boundary conditions for exterior problems.* ICASE Report No. 85-33, July 18, 1985, 33 pages. To appear in Numerical Methods for Partial Differential Equations, (S. I. Hariharan and T. H. Moulden, eds.), Pitman Press, 1986.

In this paper we consider elliptic and hyperbolic problems in unbounded regions. These problems, when one wants to solve them numerically, have the difficulty of prescribing boundary conditions at infinity. Computationally, one needs a finite region in which to solve these problems. The corresponding conditions at infinity imposed on the finite distance boundaries should dictate the boundary condition at infinity and be accurate with respect to the interior numerical scheme. Such boundary conditions are commonly referred to as absorbing boundary conditions. This paper presents a survey and covers our own treatment on these boundary conditions for wave-like equations.

Rosenau, P. and E. Turkel: *Long-time asymptotics of a system for plasma diffusion.* ICASE Report No. 85-34, July 23, 1985, 18 pages. To appear in special issue of Transport Theory and Statistical Physics.

We analyze a system of parabolic nonlinear equations that describe the diffusion of a fully collisional plasma across a strong magnetic field. We demonstrate that the solution to this system tends to a time asymptotic state which is of space-time separable form,  $\phi(t)f(x)$ . Furthermore,  $f(x)$  is independent of the initial conditions and  $\phi(t)$  depends slightly on the initial conditions. The rate of decay of the temporal part is governed by a nonlinear eigenvalue problem. Since the equations are considered in a bounded domain, we are able to analyze the effect of boundary conditions on the evolution of the system. Additional effects as radiation, heating, and particle injection can also be accounted for. Essential differences between the behavior of a fully-coupled system and a scalar equation are observed.

Adams, L.: *Reordering computations for parallel execution.* ICASE Report No. 85-35, July 24, 1985, 18 pages. Submitted to Comm. Appl. Numer. Meths.

In this paper we show how to reorder the computations in the SOR algorithm to maintain the same asymptotic rate of convergence as the rowwise ordering and to obtain parallelism at different levels. A parallel program is written to illustrate these ideas and actual machines for implementation of this program are discussed.

Noonan, R. E. and W. R. Collins: *The parser generator as a general purpose tool.* ICASE Report No. 85-36, July 31, 1985, 35 pages. Submitted to Computing Surveys.

The parser generator has proven to be an extremely useful, general purpose tool. It can be used effectively by programmers having only a knowledge of grammars and no training at all in the theory of formal parsing. Some of the application areas for which a table-driven parser can be used include interactive, query languages, menu systems, translators, and programming support tools. Each of these is illustrated by an example grammar.

Dutt, P.: *Stable boundary conditions and difference schemes for Navier-Stokes equations.* ICASE Report No. 85-37, August 1, 1985, 86 pages. Submitted to SIAM J. Numer. Anal.

The Navier-Stokes equations can be viewed as an incompletely elliptic perturbation of the Euler equations. By using the entropy function for the Euler equations as a measure of 'energy' for the Navier-Stokes equations, we are able to obtain nonlinear 'energy' estimates for the mixed initial boundary value problem. These estimates are used to

derive boundary conditions which guarantee  $L^2$  boundedness even when the Reynolds number tends to infinity. Finally, we propose a new difference scheme for modelling the Navier-Stokes equations in multidimensions for which we are able to obtain discrete energy estimates exactly analogous to those we obtained for the differential equation.

Abarbanel, S., D. Gottlieb, and E. Tadmor: *Spectral methods for discontinuous problems*. ICASE Report No. 85-38, August 9, 1985, 30 pages. Proc. of Conference on Numerical Methods for Fluid Dynamics, Reading, England.

We show that spectral methods yield high-order accuracy even when applied to problems with discontinuities, though not in the sense of pointwise accuracy. Two different procedures are presented which recover pointwise accurate approximations from the spectral calculations.

Saltz, J. H. and V. K. Naik: *Towards developing robust algorithms for solving partial differential equations on MIMD machines*. ICASE Report No. 85-39, August 10, 1985, 51 pages. Submitted to Parallel Computing.

Methods are proposed for efficient computation of numerical algorithms on a wide variety of MIMD machines. These techniques reorganize the data dependency patterns so that the processor utilization is improved.

The model problem examined finds the time-accurate solution to a parabolic partial differential equation discretized in space and implicitly marched forward in time. The algorithms investigated are extensions of Jacobi and SOR. The extensions consist of iterating over a window of several timesteps, allowing efficient overlap of computation with communication.

The methods suggested here increase the degree to which work can be performed while data are communicated between processors. The effect of the window size and of domain partitioning on the system performance is examined both analytically and experimentally by implementing the algorithm on a simulated multiprocessor system.

Hall, P.: *An asymptotic investigation of the stationary modes of instability of the boundary layer on a rotating disc*. ICASE Report No. 85-40, August 10, 1985, 29 pages. Submitted to Proc. Roy. Soc.

An investigation of high Reynolds number stationary instabilities in the boundary layer on a rotating disc is given. It is shown that in

addition to the inviscid mode found by Gregory, Stuart, and Walker (1955) at high Reynolds numbers, there is a stationary short wavelength mode. This mode has its structure fixed by a balance between viscous and Coriolis forces and cannot be described by an inviscid theory. The asymptotic structure of the wavenumber and orientation of this mode is obtained. A similar analysis is given for the inviscid mode; the expansion procedure used is capable of taking non-parallel effects into account in a self-consistent manner. The results are compared to numerical calculations and experimental observations.

Shih, K.-G. and S. S. Antman: *Qualitative properties of large buckled states of spherical shells*. ICASE Report No. 85-41, September 12, 1985, 71 pages. Submitted to Arch. Rational Mech. Anal.

A system of 6th-order quasi-linear Ordinary Differential Equations is analyzed to show the global existence of axisymmetrically buckled states. A surprising nodal property is obtained which shows that everywhere along a branch of solutions that bifurcates from a simple eigenvalue of the linearized equation, the number of simultaneously vanishing points of both shear resultant and circumferential bending moment resultant remains invariant, provided that a certain auxiliary condition is satisfied.

Brewer, D. W. and J. S. Gibson: *Parameter identification for a robotic manipulator arm*. ICASE Report No. 85-42, September 18, 1985, 24 pages. Submitted to Intl. J. Robotics.

This paper describes the development of a nonlinear dynamic model for large oscillations of a robotic manipulator arm about a single joint. Optimization routines are formulated and implemented for the identification of electrical and physical parameters from dynamic data taken from an industrial robot arm. Special attention is given to the role of sensitivity in the formulation of robust models of this motion. The importance of actuator effects in the reduction of sensitivity is established and used to develop an electro-mechanical model of the manipulator system.

Turkel, E.: *Accuracy of schemes with nonuniform meshes for compressible fluid flows*. ICASE Report No. 85-43, September 23, 1985, 48 pages. Submitted to Appl. Numer. Math.

We consider the accuracy of the space discretization for time-dependent problems when a nonuniform mesh is used. We show that many

schemes reduce to first-order accuracy while a popular finite volume scheme is even inconsistent for general grids. This accuracy is based on physical variables. However, when accuracy is measured in computational variables then second-order accuracy can be obtained. This is meaningful only if the mesh accurately reflects the properties of the solution. In addition we analyze the stability properties of some improved accurate schemes and show that they also allow for larger time steps when Runge-Kutta type methods are used to advance in time.

Bayliss, A., P. Parikh, L. Maestrello, and E. Turkel: *A fourth-order scheme for the unsteady compressible Navier-Stokes equations.* ICASE Report No. 85-44, October 2, 1985, 24 pages. AIAA Paper No. 85-1694.

A computational scheme is described which is second-order accurate in time and fourth-order accurate in space (2-4). This method is applied to study the stability of compressible boundary layers. The laminar compressible Navier-Stokes equations are solved with a time harmonic inflow superimposed on the steady state solution. This results in spatially unstable modes. It is shown that the second-order methods are inefficient for calculating the growth rates and phases of the unstable modes. In contrast the fourth-order method yields accurate results on relatively course meshes.

## ICASE COLLOQUIA

- April 1      **Professor Charles G. Speziale**, Stevens Institute of Technology: *Invariance of Subgrid-Scale Stress Models in the Large-Eddy Simulation of Turbulence*
- April 12     **Mr. P. David Stotts, Jr.**, University of Virginia: *A Hierarchical Graph Model of Concurrent Software Systems*
- April 5      **Mr. Thomas L. Jackson**, Rensselaer Polytechnic Institute: *Effects of Thermal Expansion on the Evolution and Stability of Combustion Waves*
- April 11     **Professor Koichi Oshima**, The Institute of Space and Astronautical Science, Tokyo: *Vortical Flow Interaction with Unsteady Airfoil*
- April 16     **Dr. Marios Pouagare**, Duke University: *A Multi-Sweep Space Marching Method for the Steady Navier-Stokes Equations*
- April 24     **Professor Egon Krause**, Aerodynamisches Institut, RWTH Aachen: *Initiation of Vortex Breakdown*
- April 25     **Mr. David Nicol**, University of Virginia: *Automated Partitioning of Simulations for Distributed Processing*
- April 26     **Dr. Robert G. Voigt**, ICASE: *Where are the Parallel Algorithms?*
- April 30     **Professor Arje Nachman**, Hampton University: *A Model for Intumescent Paints*
- May 3       **Dr. Shahid Bokhari**, University of Engineering, Lahore, Pakistan and ICASE: *Partitioning and Mapping Algorithms for Mesh-Connected Problems*
- May 16      **Professor Fred Habashi**, Concordia University and Pratt & Whitney: *Finite Element Method for Transonic Flow*
- May 23      **Professor Stanley G. Rubin**, University of Cincinnati: *Global Relaxation Procedures for Viscous Interacting Flows*

- June 21      **Professor Egon Krause**, Aerodynamisches Institut der RWTH, West Germany: *Slender Vortex Approximation for Compressible Flow*
- June 24      **Dr. Amiram Harten**, Tel-Aviv University and University of Wisconsin: *Non-Oscillatory High-Order Accurate Shock Capturing Schemes*
- July 8        **Professor Arne J. Pearlstein**, University of Arizona: *Calculation of Steady, Laminar Flow Past a Sphere: A First Step in Computing Transition to Vortex Shedding*
- July 23      **Dr. W. K. Buhler**, Springer-Verlag, Inc.: *Gauss as a Natural Scientist*
- August 5     **Dr. U. R. Muller**, Aerodynamic Institut, Technical University Aachen, West Germany: *Computation of Relaxing Turbulent Shear Flows by Means of Two-Equation and Reynolds-Stress Closures*
- August 26    **Professor Tsutomu Hoshino**, The University of Tsukuba, Japan: *Highly Parallel Computer PAX for Scientific Applications*
- September 19 **Mr. William B. Stamey**, Scientific Computer Systems Corporation: *The SCS-40*
- September 20 **Professor Jean Piquet**, Ecole Nationale Supérieure de Mécanique, France: *Unsteady Navier-Stokes Equations for Laminar External Flow Problems*



## ICASE SUMMER ACTIVITIES

The summer program for 1985 included the following visitors:

<b>ABARBANEL</b> , Saul, Tel-Aviv University, Israel Computational Fluid Dynamics	June 17 - September 6
<b>ADAMS</b> , Loyce, University of California, Los Angeles Numerical Methods for Parallel Computing Systems	June 17 - July 5
<b>ALAGHBAND</b> , Gita, University of Colorado Parallel Processing Systems	June 3 - July 12
<b>BANKS</b> , H. Thomas, Brown University Control Theory	June 10 - June 21
<b>BAYLISS</b> , Alvin, Exxon Corporate Research Science Laboratories Numerical Methods for Partial Differential Equations	August 19 - August 30
<b>BRANDT</b> , Achi, Weizmann Institute of Science, Israel Multigrid Methods	August 19 - August 30
<b>BURNS</b> , John A., VPI & SU University Control Theory	June 10 - June 21
<b>CROWLEY</b> , James M., U. S. Air Force Academy Control Theory	June 10 - June 21
<b>CUNY</b> , Janice E., University of Massachusetts Programming Environments for Parallel Computing Systems	June 24 - July 5
<b>EWING</b> , Richard E., University of Wyoming Numerical Methods for Inverse Problems in Distributed Systems	June 10 - June 14
<b>FALK</b> , Richard S., Rutgers University Numerical Methods for Inverse Problems in Distributed Systems	June 10 - June 14

- FULTON**, Robert E., George Washington University  
Computational Structural Mechanics May 15 - July 12
- FUNG**, Kee-Ying, University of Arizona  
Computational Fluid Dynamics July 22 - August 16
- GANNON**, Dennis, Purdue University  
Parallel Processing Systems June 24 - July 5
- GHIA**, Kirti, University of Cincinnati  
Computational Fluid Dynamics August 5 - August 30
- GHIA**, Urmilla, University of Cincinnati  
Computational Fluid Dynamics August 5 - August 30
- GIBSON**, J. Steven, University of California, Los Angeles  
Control Theory June 10 - June 21
- GOTTLIEB**, David, Tel-Aviv University and ICASE  
Numerical Methods for Partial Differential Equations June 13 - August 30
- HALL**, Philip, Imperial College, London  
Computational Fluid Dynamics July 1 - September 30
- HARIHARAN**, Subramaniya I., University of Tennessee  
Space Institute June 20 - August 2  
Computational Acoustics
- HARTEN**, Amiram, University of California, Los Angeles  
Numerical Methods for Partial Differential Equations June 17 - June 28
- HIRSCH**, Richard S., Johns Hopkins University  
Numerical Methods for Partial Differential Equations July 29 - August 9
- INMAN**, Daniel J., State University of New York  
Numerical Methods for Inverse Problems in Distributed Systems June 17 - June 21
- IPSEN**, Ilse, Yale University  
Algorithms for Parallel Systems July 8 - July 26

<b>ISRAELI</b> , Moshe, Technion, Israel Institute of Technology Computational Fluid Dynamics	July 1 - August 30
<b>ITO</b> , Kazufumi, Brown University Control Theory	June 10 - June 21
<b>JORDAN</b> , Harry F. Parallel Processing Systems	June 3 - July 12
<b>KRASNY</b> , Robert, Courant Institute Vortex Sheet Evolution	August 19 - August 30
<b>KRAVARIS</b> , Costas, University of Michigan Numerical Methods for Inverse Problems in Distributed Systems	June 17 - June 21
<b>KUNISCH</b> , Karl, Institut for Mathematik, Austria Numerical Methods for Inverse Problems in Distributed Sysems	June 10 - June 18
<b>LAMM</b> , Patricia K., Southern Methodist University Control Theory	June 17 - June 21
<b>MAJDA</b> , George, Brown University Numerical Methods for Partial Differential Equations	July 1 - July 12
<b>MCCORMICK</b> , Stephen F., Colorado State University Multigrid Methods	June 17 - June 28
<b>MEHROTRA</b> , Piyush, Purdue University Programming Languages for Multiprocessor Systems	May 20 - August 16
<b>MILLER</b> , Kevin, Purdue University Programming Languages for Multiprocessor Systems	May 20 - July 19
<b>MORGAN</b> , Kenneth, University College of Swansea, UK Multigrid Methods in Computational Fluid Dynamics	July 24 - September 4
<b>MULDER</b> , William A., Delft University of Technology Computational Fluid Dynamics	July 29 - August 30

- MURPHY**, Katherine A., Brown University  
Control Theory June 10 - June 21
- NAPOLITANO**, Michele, Universita di Bari, Italy  
Computational Fluid Dynamics July 8 - September 20
- OLIGER**, Joseph, Stanford University  
Numerical Methods for Partial Differential Equations August 5 - August 9
- PATRICK**, Merrell L.  
Algorithms for Parallel Array Computers June 17 - August 2
- POUQUET**, Annick, Universite de Nice, France  
Computational Fluid Dynamics July 1 - July 12
- PRATT**, Terrence W., University of Virginia  
Programming Languages June 24 - June 28  
July 8 - July 12
- RAVIART**, P. A., Universite Pierre et Marie Curie, France  
Particle Simulation of Fluid Flows June 27 - July 12
- REDDY**, Kapuluru C., University of Tennessee  
Space Institute August 12 - August 16  
Spectral Methods
- REED**, Daniel A., University of Illinois  
Performance of Parallel and Distributed Systems June 17 - June 28
- ROE**, Philip L., Royal Aircraft Establishment, England  
Computational Fluid Dynamics July 22 - August 9
- ROSEN**, I. Gary, University of Southern California  
Numerical Methods for Problems in Control Systems June 10 - June 21
- RUGE**, John, Colorado State University  
Multigrid Methods for Partial Differential Equations June 17 - June 28
- SCHIFF**, Bernard, Tel-Aviv University  
Finite Element Schemes Boundary Value Problems August 12 - September 6

<b>SKARR</b> , Steven, Iowa State University Numerical Methods for Control Theory	June 12 - June 21
<b>STRIKWERDA</b> , John C., University of Wisconsin Numerical Methods for Partial Differential Equations	August 12 - August 16
<b>TADMOR</b> , Eitan, Tel-Aviv University, Israel Numerical Method for Partial Differential Equations	June 17 - August 30
<b>TAL-EZER</b> , Hillel, Tel-Aviv University, Israel Numerical Methods for Partial Differential Equations	August 19 - October 18
<b>TEMAM</b> , Roger, Universite de Paris-Sud, France Numerical Methods for Partial Differential Equations	July 22 - July 26
<b>TURKEL</b> , Eli, Tel-Aviv University, Israel Computational Fluid Dynamics	July 1 - September 12
<b>VAN LEER</b> , Bram, Delft University, Netherlands Computational Fluid Dynamics	July 8 - August 2
<b>WHITE</b> , Luther W., University of Oklahoma Numerical Methods for Inverse Problems in Distributed Systems	June 10 - June 14

## OTHER ACTIVITIES

A workshop on Vortex Dominated Flows hosted by ICASE/NASA was held July 9-10, 1985. The purpose of this workshop is to bring together some of the leading experts in this field to provide an overview of our present understanding of the fluid dynamics of vortex flows. Fifteen researchers were invited to speak and their papers will be collected into a volume published by Springer. The speakers and their topics are listed below:

- F. T. Smith**, University College London: *Theory of High-Reynolds-Number Flow Past a Blunt Body*
- R. T. Davis**, University of Cincinnati: *Progress on the Calculation of Large Scale Separation at High Reynolds Numbers*
- J. C. LeBalleur**, ONERA, France: *Viscous-Inviscid Interaction Solvers and Computation of Highly Separated Flows*
- S. P. Fiddes**, Royal Aircraft Establishment, United Kingdom: *Vortical Separations from Cones at Incidence - Theory and Experiment*
- E. Murman**, Massachusetts Institute of Technology: *Study of Leading Edge Vortex Flows*
- H. W. M. Hoeijmakers**, National Aerospace Lab, The Netherlands: *Methods for Numerical Simulation of Leading-Edge Vortex Flow*
- H. K. Cheng**, University of Southern California: *A Simulation Study of Evolution, Hysteresis, and Stability of a Stationary Vortex in the Leaside of a Leading-Edge Flap*
- N. J. Zabusky**, University of Pittsburgh: *Axisymmetrization and Merger of Isolated Vortex Structures*

- D. W. Moore**, Imperial College, London: *Axisymmetric Vortex Sheets and the Formation of a Vortex Ring*
- S. Widnall**, Massachusetts Institute of Technology: *Review of Three Dimensional Vortex Dynamics; Implications for Computation of Separated and Turbulent Flows*
- L. Sirovich**, Brown University: *Comparison of Experiment with the Dynamics of the von Karman Vortex Trail*
- S. Leibovich**, Cornell University: *Waves and Instabilities in Vortex Filaments*
- J. J. Keller**, Brown Boveri Research Centre, Switzerland: *Force and Loss-Free Transitions between Vortex-Flow States*
- F. Marconi**, Grumman Aerospace: *On the Prediction of Highly Vortical Flows Using a Euler Equation Model*
- M. Hafez**, Computer Dynamics, Inc.: and **M. Salas**, NASA Langley Research Center: *A Numerical Study of Vortex Breakdown*

A Workshop on Stability of Time Dependent and Spatially Varying Flows hosted by ICASE/NASA was held August 19-20, 1985. The purpose of this workshop was to bring together some of the experts in the field for an informal exchange of ideas to update the current status of knowledge and to help identify the trends of future research. Twenty researchers were invited to speak and their papers will be collected into a volume published by Springer. The speakers and their topics are listed below:

- D.M. Bushnell**, NASA Langley Research Center: *Application of Stability Theory to Laminar Flow Control - Progress and Requirements*
- A. H. Nayfeh**, Virginia Polytechnic Institute and State University: *On Secondary Instabilities in Boundary Layers*
- A. T. Patera**, Massachusetts Institute of Technology: *Investigation of the Two- and Three-Dimensional Stability of Separated Flows by Direct Numerical Simulation Using the Spectral Element Method*
- T. Herbert**, Virginia Polytechnic Institute and State University: *Floquet Analysis of Secondary Instability in Shear Flows*
- R. J. Bodonyi**, Purdue University: *On Short-Scale Inviscid Instabilities in Flow Past Surface-Mounted Obstacles*
- F. T. Smith**, University College, London: *Non-linear Effects and Non-parallel Flows*
- S. G. Lekoudis**, Georgia Institute of Technology: *The Stability of the Boundary Layer on an Ellipsoid of Revolution*
- C. von Kerczek**, Catholic University of America: *Stability Characteristics of Some Oscillatory Flows - Poiseuille, Ekman and Films*



- P. A. Monkewitz**, University of California, Los Angeles: *The Stability of the Stokes Layer: Visual Observations and Some Theoretical Considerations*
- S. Cowley**, University College, London: *High Frequency Rayleigh Instabilities in Time-Dependent Boundary Layer Flows*
- L. Mack**, California Institute of Technology: *Review of Linear Compressible Stability Theory*
- A. Bayliss**, Exxon Corporate Research: *Active Control and Nonlinear Stability of Compressible Flows*
- P. Hall**, Imperial College, London: *Instability of Time-Periodic Flows*
- T. Gatski**, NASA Langley Research Center: *Numerical Experiments on Boundary Layer Receptivity*
- D. R Williams**, Illinois Institute of Technology: *Vortical Structures in the Breakdown Stage of Transition*
- D. Benney**, Massachusetts Institute of Technology: *A New Approach to Hydrodynamic Instabilities*
- M. Goldstein**, NASA Lewis Research Center: *The Generation of Tollmien-Schlichting Waves by External Disturbances*
- R. Kelly**, University of California, Los Angeles: *Thermal Convection with Horizontal and Vertical Temperature Gradients*
- C. Streett**, NASA Langley Research Center: *The Effect of Finite Length on Taylor-Couette Flow*
- L. Sirovich**, Brown University: *Studies of the Ginzburg-Landau Equation*

## ICASE STAFF

### I. ADMINISTRATIVE

Milton E. Rose, Director  
Ph.D., Mathematics, New York University, 1953  
Numerical Methods

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Ph.D., Mathematics, University of Maryland, 1969  
Numerical and Computational Techniques

Linda T. Johnson, Administrative Assistant

Etta M. Blair, Personnel/Bookkeeping Secretary

Juanita L. Fisher Office Assistant (Beginning August 1985)

Juanita L. Jones, Office Assistant (Beginning March 1985)

Barbara A. Kraft, Senior Technical Publications Secretary

Emily N. Todd, Visitor Coordinator/Correspondence Secretary

Georgia A. Voss, Technical Publications/Summer Housing Secretary

### II. SCIENCE COUNCIL for APPLIED MATHEMATICS and COMPUTER SCIENCE

Bruce Arden, Chairman and Arthur Doty Professor, Department of Electrical Engineering and Computer Science, Princeton University.

Andrew J. Callegari, Director, Theoretical & Mathematical Sciences Laboratory, Exxon Research & Engineering Company.

Peter Denning, Director, RIACS, NASA/Ames Research Center.

Michael J. Flynn, Professor, Department of Electrical Engineering, Computer Systems Laboratory, Stanford University.

Bernard Galler, Professor, Department of Computer and Communication Sciences and Associate Director of the Computer Center, University of Michigan.

Anthony C. Hearn, Department Head, Department of Information Sciences, Rand Corporation.

Herbert Keller, Professor, Physics, Math, and Astronomy, California Institute of Technology.

Seymour V. Parter, Professor, Department of Mathematics, University of Wisconsin.

Werner C. Rheinboldt, Andrew W. Mellon Professor, Department of Mathematics and Statistics, University of Pittsburgh.

Milton E. Rose, Director, Institute for Computer Applications in Science and Engineering, NASA Langley Research Center.

### III. ASSOCIATE MEMBERS

Saul S. Abarbanel, Professor, Department of Applied Mathematics, Tel-Aviv University, Israel.

H. Thomas Banks, Professor, Division of Applied Mathematics, Brown University.

Peter D. Lax, Professor, Courant Institute of Mathematical Sciences, New York University.

William R. Sears, Professor, Department of Aerospace and Mechanical Engineering, University of Arizona.

### IV. SENIOR STAFF SCIENTISTS

David Gottlieb - Ph.D., Numerical Analysis, Tel-Aviv University, Israel, 1972. Professor, Department of Applied Mathematics, Brown University. Numerical Methods for Partial Differential Equations. (July 1974 to January 1987)

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### V. SCIENTIFIC STAFF

Stephen F. Davis - Ph.D., Applied Mathematics, Rensselaer Polytechnic Institute, 1980. Numerical Methods for Partial Differential Equations. (February 1982 to September 1985)

Pravir Dutt - Ph.D., Mathematics, University of California, Los Angeles, 1985. Numerical Analysis related to Navier-Stokes Equations. (July 1985 to June 1987)

Eduard Harabetian - Ph.D., Mathematics, University of California, Los Angeles, 1984. Mathematical Analysis of Numerical Algorithms for Nonlinear Partial Differential Equations. (October 1984 to September 1985)

Murshed Hossain - Ph.D., Physics, College of William and Mary, 1983. Fluid Turbulence. (December 1983 to June 1985)

Liviu Lustman - Ph.D., Applied Mathematics, Tel-Aviv University, Israel, 1979. Numerical Methods for Partial Differential Equations, Spectral Methods, Computational Fluid Dynamics. (August 1984 to September 1986)

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David M. Nicol - Ph.D., Computer Science, University of Virginia, 1985. Techniques for Mapping Algorithms onto Parallel Computing Systems. (September 1985 to August 1987)

Robert K. Powers - Ph.D., Applied Mathematics, Virginia Polytechnic Institute and State University, 1984. Numerical Techniques for Optimal Control. (March 1984 to September 1986)

Georg Propst - Ph.D., Mathematics-Functional Analysis, Karl Franzens Universitat, Austria, 1985. Linear Quadratic Control Problem for Delay Systems. (September 1985 to August 1987)

Joel H. Saltz - Ph.D., Computer Science, Duke University, 1985. Analysis of Parallel Methods for Time Dependent Partial Differential Equations. (July 1985 to September 1986)

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## VI. VISITING SCIENTISTS

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Achi Brandt - Ph.D., Numerical Methods, Weizman Institute of Science, Israel, 1965. Professor, The Weizman Institute, Israel. Multigrid Methods. (August 1985)

Dennis W. Brewer - Ph.D., Applied Mathematics, University of Wisconsin-Madison, 1975. Associate Professor, Mathematical Sciences, University of Arkansas. Control Theory. (June 1984 to August 1985)

Shahid H. Bokhari - Ph.D., Electrical and Computer Engineering, University of Massachusetts, Amherst, 1978. Associate Professor, Department of Electrical Engineering, University of Engineering and Technology, Lahore, Pakistan. Parallel Processing, Distributed Computing and Computer Architecture. (July 1984 - June 1986)

Richard E. Ewing - Ph.D, Mathematics, University of Texas at Austin, 1974. Professor, Department of Mathematics and Petroleum Engineering, University of Wyoming. Numerical Methods for Inverse Problems in Distributed Systems. (June 1985)

Richard S. Falk - Ph.D., Applied Mathematics, Cornell University, 1971. Professor, Department of Mathematics, Rutgers, University. Numerical Methods for Inverse Problems in Distributed Systems. (June 1985)

Robert E. Fulton - Ph.D., Structural Mechanics, University of Illinois, 1960. Senior Staff Scientist, Department of Civil and Mechanical Engineering, George Washington University. Computational Techniques for Problems Related to Structural Mechanics. (May - July 1985)

Kee-Yung Fung - Ph.D., Aeronautical Engineering, Cornell University, 1976. Associate Professor, Department of Aerospace and Mechanical Engineering, University of Arizona. Numerical Investigation of the Stability of Leading Edge Separation. (July - August 1985)

Kirti N. Ghia - Ph.D., Aerospace Engineering, Illinois Institute of Technology, 1969. Professor, Department of Aerospace Engineering and Mechanics, University of Cincinnati. Computational Fluid Dynamics. (August 1985)

Urmilla Ghia - Ph.D., Control Theory, Illinois Institute of Technology, Chicago, 1971. Professor, Department of Mechanical and Industrial Engineering, University of Cincinnati. Computational Fluid Dynamics. (August 1985)

Philip Hall - Ph.D., Mathematics, Imperial College, England, 1973. Professor, Department of Applied Mathematics, University of Exeter, England. Computational Fluid Dynamics. (July - September 1985)

Richard S. Hirsch - Ph.D., Fluid Mechanics, Case Western Reserve University, 1971. Senior Staff Scientist, Applied Physics Laboratory, Johns Hopkins University. Numerical Methods for Partial Differential Equations. (July - August 1985)

Daniel Inman - Ph.D., Mechanical Engineering, Michigan State University, 1980. Associate Professor, Department of Mechanical and Aerospace Engineering, State University of New York at Buffalo. Numerical Methods for Inverse Problems in Distributed Systems. (June 1985)

Ilse Ipsen - Ph.D., Computer Science, The Pennsylvania State University, 1983. Assistant Professor, Department of Computer Science, Yale University. Algorithms for Parallel Systems. (July 1985)

Moshe Israeli - Ph.D., Applied Mathematics, Massachusetts Institute of Technology, 1971. Visiting Associate Professor, Department of Mechanical Aerospace Engineering Science (Computational and Applied Mathematics Program), Princeton University. Computational Fluid Dynamics. (December 1984 - August 1985)

Robert Krasny - Ph.D., Applied Mathematics, University of California at Berkeley, 1983. NSF Fellow, Courant Institute, New York University. Vortex Sheet Evolution. (August 1985)

Costas Kravaris - Ph.D., Chemical Engineering, California Institute of Technology, 1984. Assistant Professor, Department of Chemical Engineering, The University of Michigan. Numerical Methods for Inverse Problems in Distributed Systems. (June 1985)

George Majda - Ph.D., Numerical Analysis, New York University, 1980. Assistant Professor, Department of Applied Mathematics, Brown University. Numerical Methods for Partial Differential Equations. (July 1985)

Stephen F. McCormick - Ph.D., Mathematics, University of Southern California, 1971. Professor, Department of Mathematics, Computational Mathematics Institute, Colorado University - Denver. Multigrid Methods for Partial Differential Equations. (June 1985)

Piyush Mehrotra - Ph.D., Computer Science, University of Virginia, 1982. Assistant Professor, Department of Computer Science, Purdue University. Programming Languages for Multiprocessor Systems. (May - August 1985)

Kenneth Morgan - Ph.D., Applied Mathematics, Bristol, England, 1970. Senior Lecturer, Institute for Numerical Methods In Engineering, University of Wales, United Kingdom. Multigrid Methods in Computational Fluid Dynamics. (July - September 1985)

William A. Mulder - Ph.D., Astronomy, University of Leiden, 1985. Postdoctoral Fellow, Department of Computer Science, Stanford University. Computational Fluid Dynamics. (August 1985)

Michele Napolitano - Ph.D., Aerospace Engineering, University of Cincinnati, 1970. Professor, Istituto Di Macchine, University of Bari, Italy. Incremental Multigrid Methods for Compressible Navier-Stokes Equations. (July - September 1985)

Robert E. Noonan - Ph.D., Computer Science, Purdue University, 1971. Professor, Department of Computer Science, College of William and Mary. Computer Systems, Multi-Processors. (September 1984 - May 1985)

Merrell L. Patrick - Ph.D., Mathematics, Carnegie-Mellon University, 1964. Professor, Department of Computer Science, Duke University. Algorithms for Parallal Array Computers. (June - August 1985)

Annick Pouquet - Ph.D., Physics, University of Nice, France, 1976. Chargie a le Recherches, CNRS, Observatoire de Nice, France. Computational Fluid Dynamics. (July 1985)

Pierre A. Raviart - Ph.D., Mathematics, University of Paris, 1965. Professor, Department of Mathematics, Pierre et Marie Curie, France. Particle Simulation of Fluid Flows. (July 1985)

Kapuluru C. Reddy - Ph.D., Applied Mathematics, Indian Institute of Technology, Kharagpur, India, 1965. Professor, Department of Mathematics, University of Tennessee Space Institute. Spectral Methods. (August 1985)

Philip L. Roe - Ph.D., Cambridge University, 1962. Professor, Department of Computational Fluid Dynamics, Cranfield Institute of Technology, England. Computational Fluid Dynamics. (July - August 1985)

John W. Ruge - Ph.D., Mathematics, Colorado State University, 1981. Research Mathematician, Computational Mathematics Institute, Colorado University - Denver. Multigrid Methods of Partial Differential Equations. (June 1985)

Bernard Schiff - Ph.D., Mathematics, University of London, England, 1955. Senior Lecturer, Department of Applied Mathematics, Tel Aviv University, Israel. Finite Element Schemes for Elliptic Boundary Value Problems. (August - September 1985)

Steven B. Skaar - Ph.D., Engineering Mechanics, Virginia Polytechnic Institute and State University, 1982. Assistant Professor, Department of Engineering Science and Mechanics, Iowa State University. Numerical Methods of Control Theory. (June 1985)

Eitan Tadmor - Ph.D., Numerical Analysis, Tel-Aviv University, 1979. Senior Lecturer, Department of Applied Mathematics, Tel-Aviv University, Israel. Numerical Methods for Partial Differential Equations. (June - September 1985)

Hillel Tal-Ezer - Ph.D., Applied Mathematics, Tel-Aviv University, 1985. Ph. D., Department of Mathematics, Tel-Aviv University, Israel. Spectral Methods for Partial Differential Equations. (September - October 1985)

Roger Temam - Ph.D., Numerical Analysis, University of Paris, 1967. Professor, Department of Mathematics, Universite Paris XI, France. Computational Fluid Dynamics. (July 1985)

Eli Turkel - Ph.D., Applied Mathematics, New York University, 1970. Associate Professor, Department of Applied Mathematics, Tel-Aviv University, Israel. (January - December 1985)

Bram van Leer - Ph.D., Theoretical Astrophysic, Leiden State University, 1970. Research Leader, Department of Applied Mathematics and Computer Science, Delft University of Technology, Netherlands. Computational Fluid Dynamics. (July - August 1985)

Luther W. White - Ph.D., Mathematics, University of Illinois, Champaign-Urbana, 1977. Professor, Department of Mathematics, University of Oklahoma. Numerical Methods for Inverse Problems in Distributed Systems. (June 1985)

## VII. CONSULTANTS

Loyce M. Adams - Ph.D., Applied Mathematics, University of Virginia, 1983. Parallel Numerical Algorithms. Associate Professor, Department of Applied Mathematics, University of Washington. Numerical Methods for Parallel Computing Systems.

Ivo Babuska - Ph.D., Technical Sciences, Tech University, Prague, Czechoslovakia, 1952; Mathematics, Academy of Sciences, Prague, 1956; D.Sc., Mathematics, Academy of Science, Prague, 1960. Professor, Institute for Physical Science and Technology, University of Maryland. Numerical Methods for Partial Differential Equations.

Alvin Bayliss - Ph.D., Mathematics, New York University, 1975. Senior Staff Scientist, Exxon Corporate Research. Numerical Methods for Partial Differential Equations.

Marsha J. Berger - Ph.D., Numerical Analysis, Stanford University, 1982. Research Associate, Courant Institute of Mathematical Sciences. Numerical Methods for Partial Differential Equations.

Dennis W. Brewer - Ph.D., Mathematics, University of Wisconsin, Madison, 1975. Associate Professor, Department of Mathematical Sciences, University of Arkansas. Methods for Parameter Identification and Estimation.



John A. Burns - Ph.D., Mathematics, University of Oklahoma, 1973. Professor, Virginia Polytechnic Institute and State University. Numerical Methods in Feedback Control and Parameter Estimation.

James M. Crowley - Ph.D., Applied Mathematics, Brown University, 1982. Assistant Professor, Department of Mathematics, (Captain), U.S. Air Force Academy. Identification for Distributed Parameter Systems.

Janice E. Cuny - Ph.D., Computer Science, University of Michigan, 1981. Assistant Professor, Department of Computer and Information Science, University of Massachusetts. Program Environments for Parallel Computing Systems.

Peter R. Eiseman - Ph.D., Mathematics, University of Illinois, 1970. Senior Research Scientist and Adjunct Professor, Department of Applied Physics and of Nuclear Engineering, Columbia University. Computational Fluid Dynamics.

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